Comparison of movements in a virtual reality mirror box therapy for treatment of lower limb phantom pain

Henriksen, Bartal; Nielsen, Ronni Nedergaard; Kraus, Martin; Geng, Bo

Published in:
Proceedings of the 13th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications

DOI (link to publication from Publisher):
10.5220/0006537801670174

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Henriksen, B., Nielsen, R. N., Kraus, M., & Geng, B. (2018). Comparison of movements in a virtual reality mirror box therapy for treatment of lower limb phantom pain. In D. Bechmann, A. P. Claudio, & J. Braz (Eds.), *Proceedings of the 13th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications* (Vol. 1, pp. 167-174). SCITEPRESS Digital Library. https://doi.org/10.5220/0006537801670174

Comparison of Movements in a Virtual Reality Mirror Box Therapy for Treatment of Lower Limb Phantom Pain

Bartal Henriksen[1], Ronni Nedergaard Nielsen[1], Martin Kraus[2] and Bo Geng[3]
[1]School of Information and Communication Technology, Aalborg University, Rendsburggade 14, Aalborg, Denmark
[2]Department of Architecture, Design and Media Technology, Aalborg University, Rendsburggade 14, Aalborg, Denmark
[3]Department of Health Science and Technology, Aalborg University, Fredrik Bajers Vej 7, Aalborg, Denmark

Keywords: Virtual Reality, Phantom Limb Pain, Mirror Box Therapy.

Abstract: Many patients experience Phantom Limb Pain (PLP) after an amputation. Traditional Mirror Box Therapy (MBT) has proven efficient for some patients, but the movements in MBT are physically limited, for lower limb amputees. In this work, we investigated how anti-symmetrical mirroring compares to regular mirroring in Virtual Reality (VR) MBT for lower limb amputees, as natural leg movements are anti-symmetrical, like walking, running, and cycling. To motivate the patients, a game was developed that uses cycling and swinging movements. We implemented the required movements into a goal-oriented game where the patient must fly a gyrocopter through goal areas. The experiment was implemented as a within-subject design, where the participants had to try three versions of the game and give preferential feedback. The findings showed that the cycling version was more exhausting than the anti-symmetrical and symmetrical swinging versions. Furthermore, we discovered that the required cycling motions were too difficult and tiresome to do over a longer period of time. On the other hand, we found that it is possible to use anti-symmetrical swinging of legs in VR MBT.

1 INTRODUCTION

When people have a limb amputated due to accident or surgery, a condition called Phantom Limb Pain (PLP) can occur. PLP is the pain experienced in the amputated limb and occurs for up to 85% of all amputees (Kooijman et al., 2000; Sherman, Sherman and Parker, 1984). The PLP can relate to a certain movement or position of the phantom limb, as well as physical factors, such as: weather changes or pressure on the residual limb (Flor, 2002). PLP is not the same as physical pain and therefore the same treatments, such as local anaesthesia and muscle relaxant, are not effective for it (Flor, 2002). Different hypotheses to why PLP occurs have been explored, but the reason is still not known.

However, a method called Mirror Box Therapy (MBT) has shown promising results in reducing PLP for some patients (Ramachandran and Rogers-Ramachandran, 1996). The MBT works by providing the patients with an illusion that they regain the missing limb. This is achieved by placing a mirror perpendicular to the patient. The intact limb is then mirrored onto the phantom limb. If positioned correctly, this creates the illusion that the amputated limb is still present. Why MBT is successful is unclear, but one speculation is that mirror illusion resolves the conflict between missing visual feedback and movement intention, which might cause PLP (Flor, 2002; Ramachandran and Hirstein, 1998). The MBT is used both for lower limb and upper limb amputees. In the MBT for lower limb amputees, more requirements are needed to establish the illusion. The patient needs to sit on a bed or a couch and must look into a mirror from a specific angle to establish the illusion. If the patient moves or looks away, the illusion breaks down. The patient further has limited movement, as the sitting position requires them to bend forward to look into the mirror, while putting their weight onto the leg.

1.1 Related Work

While the traditional MBT has produced promising results for treatment of PLP, there are potential advantages of developing a virtual MBT concept. In a virtual environment (VE), there are less physical restrictions to maintain the illusion of the virtual

Henriksen, B., Nielsen, R., Kraus, M. and Geng, B.
Comparison of Movements in a Virtual Reality Mirror Box Therapy for Treatment of Lower Limb Phantom Pain.
DOI: 10.5220/0006537801670174
In *Proceedings of the 13th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2018) - Volume 1: GRAPP*, pages 167-174
ISBN: 978-989-758-287-5

limb in the mirror, as the patient does not need to sit in a fixed position. Furthermore, virtual MBT also enables the possibility to apply the MBT exercises into more meaningful tasks and in more motivating environments, such as games.

The concept of a virtual MBT has been explored in the past decade, together with the advancing technologies in motion sensors and the use of head-mounted displays (HMDs) for depth perception in virtual and/or augmented environments. Several virtual MBT concept proposals have been developed and a few systems have been tested with PLP patients. These concepts use an HMD or custom made display setups to visualize the system, and while most concepts use a Virtual Reality (VR) representation (Cole et al., 2009; Murray et al., 2006; Osumi et al., 2017; Sato et al., 2010; Zweighaft et al., 2012), a few have also developed augmented reality systems that implement a virtual limb to a representation of the stump of the patient (Ortiz-Catalan et al., 2014; Trojan et al., 2013). To track the movements of the patients, several systems have been proposed, such as applying motion-detection gloves, motion sensors, or pre-rendered motions. The tested systems have shown promising results, as the patients have experienced increased control of the phantom limb by using some these systems (Cole et al., 2009; Murray et al., 2006; Osumi et al., 2017), and others have experienced a short-term reduction in pain (Osumi et al., 2017; Sato et al., 2010) as a result of the VR experiences.

In MBT, the exercise types used by the patients vary depending on the pain and disability state of individual patients (Brodie et al., 2003). For upper-limb amputees the exercises include finger movements, hand rotations and arm movements. The patient usually starts with a small basic movement. The movement is then repeated until the patient feels comfortable and ready for a more challenging move. A similar approach is used for lower-limb amputees. The exercises consist of bending the knee, moving the foot, rotating the ankle and toe movements (Brodie, Whyte and Waller, 2003).

Even though the amount of lower-limb amputees is a lot higher than upper-limb amputees (Brodie, Whyte and Waller, 2003), most studies have focused on developing different meaningful movements for upper-limb amputees, such as: basic movement of the upper limb (Murray et al., 2006; Ortiz-Catalan et al., 2014; Osumi et al., 2017), punching an object (Murray et al., 2006), grabbing and releasing objects (Cole et al., 2009; Sato et al., 2010; Zweighaft et al., 2012) and flexing the fingers (Trojan et al., 2013). But there have only been a limited set of meaningful movements explored for lower-limb amputees, such as kicking an object or tapping a drum pedal (Cole et al., 2009; Murray et al., 2006). Furthermore, while the concepts proposed try to apply meaningful movements to the MBT exercises, most focus on applying standard mirrored movements. This makes sense as mirrored movements often occur when using both upper-limbs at the same time. The movements used with the phantom limb in the MBT, have a greater effect if they “feel” natural for the patient for them to be convinced they are moving their phantom limb (Henriksen et al., 2016). In this study, three different mirrored applications were developed: (1) grabbing and releasing boxes, (2) pressing mirrored buttons and (3) a “bending game” in which the patient had to bend a virtual rod with both hands into different angles. While all three versions were able to apply meaningful movements, only the bending game was able to activate the feeling of using the phantom upper-limb when tested on an amputee (Henriksen et al., 2016). Based on these results, it was hypothesized that by applying mirrored movements, which required the use of both lower-legs would help lower-limb patients feel they used both their intact and phantom leg, when playing the games (Nielsen et al., 2017). Nielsen et al. developed two different games: (1) a shape game, where the user needed to move both feet into symmetrical square boxes in different angles, and (2) a slingshot game, where the user needed to grab the handle of a slingshot by doing a grabbing motion with their toes, aim the handle by moving their feet and release the handle by releasing their toes. However, following an experiment with healthy subjects and a test with a lower-leg amputee, it was discovered that the mirroring movements were not enough, as the movements were either too abstract or too mundane (Nielsen et al., 2017). It should be noted that this experiment also indicated the games were constraining to do as they required the participants to move their legs up in the air, in order to do the required movements. Therefore, in order to develop a VR MBT concept that encourages the use of both lower-limbs, the concept must use motions that feel natural to do with both legs. Furthermore, the setup needs to be designed so it does not constrain the legs of the user, as these constraints would interfere with the overall experience and may stop the user from using both legs.

While the long term goal is to design a VR version of MBT to alleviate PLP, the goal for this work is to encourage movement of both legs, and engage users by having them play a game while using both legs. The focus of this work is on lower-limb amputees and anti-symmetrical movements

2 METHOD

To compare symmetrical and anti-symmetrical movements, a system using VR technology that applied mirroring methods other than standard mirroring for lower-limb MBT was developed. The system uses a HTC Vive Head-Mounted Display (HMD) to visualise the virtual environment. The two HTC Vive controllers are attached to the left leg of the participants in specific positions: one on the thigh above the leg and one on top of the foot as seen in Figure 1.

Figure 1: The setup of the experiment. The participant is viewing the game through the HMD while controlling the avatar through the two controllers attached to the left leg.

Through this setup, the user is able to control a high detailed virtual avatar within the VE which is positioned in the same position as the user. Two avatar models were available; a male and a female. The avatar is positioned so the user views the avatar from the head position and is adjusted in size to fit the user prior to game start. The virtual upper body follows the HMD position while the pelvis is stationary in a seated position. The controlled leg follows the sensory input from the two controllers, while the other leg moves based on one of three movement: two anti-symmetrical movements and a regular mirrored version for comparison: (1) Anti-symmetrical swinging version: This version is based on a simple anti-symmetrical movement, such as walking, as the user needs to move the controlled leg in a back and forward swinging motion. The mirrored limb then follows this motion in an anti-symmetrical manner. (2) Cycling version: This anti-symmetrical version is based on applying cycling motions. Here, the user needs to perform circular motions with the controlled leg. The mirrored leg then performs inverted movements, so the leg will do anti-symmetrical movements both in the up/down and forward/backwards directions. (3) Symmetrical swinging version: In this version the user needs to move the controlled leg in a back and forward motion, similar to the anti-symmetrical version. However, here the mirrored leg follows this motion. The purpose of this version is to use as a control version for comparison. The user perspective of the avatar within the VE can be seen in Figure 2.

Figure 2: The avatar representation in the game. Left: the field of view of the user; right: illustration of how the avatar is seated in the gyrocopter.

When the games starts, the user applies one of the movements to control the virtual avatar. Whenever the user applies half a cycle of the given movement, the altitude of the gyrocopter is increased. If no movement is applied, the gyrocopter slowly starts losing altitude. The gyrocopter moves forward automatically in a steady pace. The user is motivated to apply these movements correctly and in a timely fashion in order to hit yellow transparent checkpoints throughout the game in order to get as menu checkpoints as possible before the finish line. The three leg movements each apply the same amount of altitude and the level is the same for each iteration.

3 EVALUATION

This experiment was conducted with 18 participants (aged 21 to 27, mean 25.9 years, 5 females and 13 males). The participants were mainly university students from various educations. All participants had at least some experience with using Virtual Reality prior to this experiment. The experiment was conducted as a within-subject design as all participants were instructed to play through all three versions of the game. The order of the versions was randomized in a counterbalanced order, to remove any carry-over effects. Besides determining the exertion rate of the three versions, another focus in this experiment was to evaluate how much the users applied movement to both legs, to find out if the versions encouraged movement of both legs. Furthermore, the anti-symmetrical movements, which are not applicable in a standard MBT session, were compared to the symmetrical version. Therefore, this work focused on evaluation of the two following aspects:

(1) The exertion rate of each movement was measured, following the completion of the level for each movement version.

(2) The amount of movement applied to both legs during each version of the game were evaluated, in order to compare the two anti-symmetrical versions to the mirrored version.

3.1 Setup

The participant of the experiment sits on the edge of a high table when playing through the three iterations of the game in order to reduce the amount of constrains in the legs. They are equipped with two HTC Vive controllers on the left leg and attached the HMD thereafter. It was decided to apply sensor controls to only the left leg in order to avoid an internal validity conflict as having sensors on both legs could encourage the participants to apply movement to both. Instead a camera setup was used to record the leg movements for all participants in each iteration. The footage was used to check if the participants used one or both legs to apply the movement cycles and to count how many of each movement cycles were applied. It should be noted that only a complete cycle using both legs counted as an accepted applied movement cycle. Following the completion of a single playthrough, the participants answered questionnaires concerning the exertion rate of the given version through a Borg rating scale, and to rate the leg movements through Likert-scale questions.

3.2 Procedure

The participants were initially instructed to sign a consent form and to read a short description of the test which included instructions on how to control the gyrocopter using the three different movement versions and an overview of the different features in the panel of the gyrocopter. The description further clarified the possibility to play the game using either one or both legs, to reduce bias towards one approach. The participants were hereafter equipped with the controllers and HMD, and be seated in the correct position. Following the introductory part, the participants would complete the same game in each of the three iterations, in a counterbalanced order. Completion of the level took about 3.5 minutes. Following each version, the participants were instructed to complete a questionnaire, to get the exertion results while they were still in their recent memory and to get a short break from the game. After all three game iterations were completed, the participants completed the post-questionnaire.

4 RESULTS

The symmetrical and anti-symmetrical swinging versions did not have a high exertion rate as their respective mean value were 9.06 for the symmetrical and 9.56 for the anti-symmetrical version, with 9 being relative to walking slowly, as seen in Figure 3. The cycling version however received a mean answer of 13.39, which is about "hard, but manageable" and a median of 14. Following each iteration, the participants were instructed to explain if they experienced any discomfort during the level. In the symmetrical and anti-symmetrical swinging versions, two participants experienced discomfort, while 16 did not. In the cycling version, ten participants explained they felt a type of discomfort, while eight did not. The main discomfort types included: (1) strained muscles, (2) sweating under the head-mounted display and (3) sweating in general. No participants experienced nausea in any of the three versions.

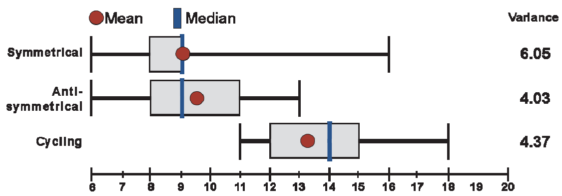

Figure 3: The exertion of each of the three versions, based on a BORG scale rating.

Following the three iterations of the game the participants were instructed to rank the three versions in terms of exhaustion. They were asked to rank the three versions from (1) least exhausting, (2) second most exhausting and (3) most exhausting. As seen in Figure 4, the symmetrical version was chosen as the least exhausting version with 11 choosing this version and 6 choosing the anti-symmetrical swinging version. This corresponds with the exertion rate data, as the symmetrical and anti-symmetrical swinging versions are rated close to each other in the Borg scale for the exertion rate, but with the symmetrical version being less exhausting. The cycling version was ranked as the most exhausting version by 17 of 18 participants, which also corresponds with the results from the Borg scale.

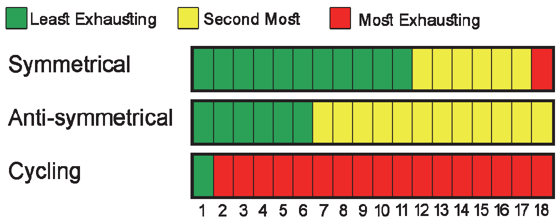

Figure 4. The three versions ranked in terms of exhaustion, ranked from (1) least exhausting, (2) second most and (3) most.

4.1 Leg Movements

The leg movements of the participants were filmed to evaluate the use of both legs during each of the three versions of the game. In each version, the number of completed cycles were counted, and split into either "one leg" counters or "both leg" counters. The results from the data set includes: (1) Symmetrical swinging: In the symmetrical version both legs were used overall 92.5% of the time, as 15 of the participants used both legs for all cycles, and two used both legs during most of the cycles and one used both legs in only 8.3% of the time, as seen in Table 1, row (1). It was further noted that three participants alternated between using the correct symmetrical movements to anti-symmetrical movements in some cases, either in the beginning of the level or when having to apply a high pace. (2) Anti-symmetrical swinging: Overall the participants used both legs 88.4% of the time during the anti-symmetrical movements, as seen in Table 1, row (2). Here, 13 of the participants used both legs at all times, while three used both more than half of the time and two only used both in about ⅓ of the time. One participant was noted applying symmetrical movements in the beginning, but changed to the correct anti-symmetrical movements after a short while. (3) Cycling: Overall both legs were used 96% of the time as 15 participants used both legs all the time and 3 used both legs more than half of the time. One participant only used one leg in one cycle, while using both legs in higher paced areas. Even though many used both legs, how they used the legs varied. Two participants applied small circular motions, while two applied flat swinging motions which looked close to the anti-symmetrical motions. Finally, one participant applied motions that looked similar to running motions.

Since the data is not normally distributed, a Friedman's test was used to compare the results. The use of both legs for the participants was not significantly different between the three versions, $2(2) = 0.89$, $p > .05$ ($p = 0.64$). Following each version, the participants were instructed to evaluate the leg movements through five Likert-scale questions ranked from 1: strongly disagree to 7: strongly agree. The participants found the leg movements required in the symmetrical and anti-symmetrical swinging versions easy to perform as the mean answers were 6.22 and 6.33 respectively with 17 of 18 participants agreeing in both questions, as seen in Figure 5. The cycling version received a mean answer of 4.37, which indicate the participants did not feel the cycling version was particularly easy to perform.

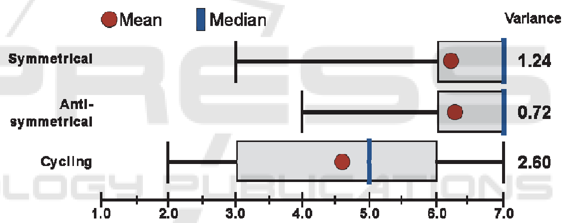

Figure 5: Question (1): "I found the leg movements easy to perform".

When asked if the symmetrical and anti-symmetrical swinging movements felt natural to perform the mean answer was 5.89 for both answers, as seen in Figure 6, which indicates the participants felt these versions were natural to perform. However, the cycling version received mixed answers with a mean of 4.22 and a large variance of 3.71, which indicates not everyone found the cycling movements natural.

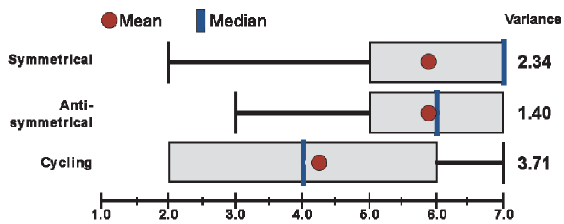

Figure 6: Question (2): "The leg movements felt natural to perform".

When asked if the leg movements felt consistent with their real leg movements, the symmetrical version received a mean answer of 6.11 and the anti-symmetrical swinging version 6.00, as seen in Figure 7. Furthermore, in both versions 17 of 18 participants agreed to some degree on this question. The cycling version generally got positive results as the mean answer was 5.11 and 13 agreeing to some degree.

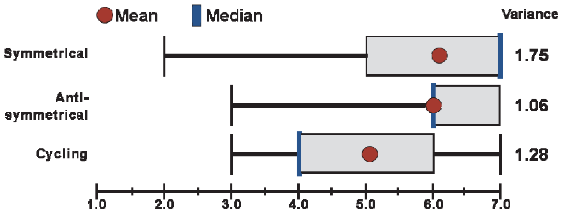

Figure 7: Question (3): "The leg movement felt consistent with my real leg movement(s)".

4.2 Game Data

Following the three iterations of the game, the participants were instructed to rank the games as (1) favorite version, (2) second favorite and (3) least favorite version. As seen in Figure 8, the anti-symmetrical swinging version was the favorite game version, as 11 chose this as their favorite and six chose it as their second favorite. The cycling was their least favorite, with 14 choosing this version as their least favorite game version.

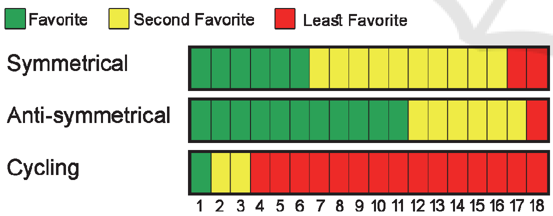

Figure 8: The preferred versions, ranked by (1) favorite version, (2) second favorite version and (3) least favorite version.

5 DISCUSSION

The participants used both legs to a high degree in all three versions and there was no significant difference between the three versions in this regard.

This indicates that all versions do encourage the use of both legs. However, as the experiment was conducted using only healthy participants, the high usage of both legs could be influenced by predefined proprioceptive patterns within the participants, i.e. they are used to applying these movements in real life. With amputees the high degree of movement may be lower as some amputees are not used to apply movements with both limbs. However, as many amputees are walking using prosthesis, or doing swimming exercises and similar, these movement patterns are not completely unfamiliar. Furthermore, the high degree also shows that the movements are intuitive to apply, which would help encourage the use of both limbs for amputees and thus help reduce phantom pain.

As the three versions controlled the gyrocopter through the same system, the results indicate that applying the cycling motions was a lot harder, compared to the other two versions. One reason for the high exertion rate for the cycle game could be the increased amount of movements overall, as the participants needed to lift their legs besides applying the swinging motions. Furthermore, it was noted that the participants used different approaches to apply the cycling motions; some applied small circular motions and did well in the game, while others would apply very flat cycling motions which did not help performing the cycle correctly. A reason for the difficulties applying the cycling motion could be of the lack of physical pedals. It should also be noted that the large variability within how the participants applied the motions could have had an effect on the overall result, as the exertion rate differed greatly between these approaches.

Regarding the symmetrical and anti-symmetrical swinging versions, both received a low exertion rate score on the Borg scale, with the symmetrical version being marginally lower. However, the anti-symmetrical version was favored by most participants. Furthermore, it should be noted that

Table 1: How much both legs were used in full cycles, in percentage. First line (1) is the symmetrical version, (2) anti-symmetrical and (3) is the cycling version.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
(1)	100	8.3	100	100	100	81.4	100	100	100	100	73	100	100	100	100	100	100	100
(2)	100	100	100	100	89.1	50.6	100	100	77.1	100	100	100	37.4	100	36.1	100	100	100
(3)	100	87.3	100	100	64.8	100	100	77.1	100	100	100	100	100	100	100	100	100	100

some participants would change from symmetrical to anti-symmetrical movements within the same level. This could indicate that the anti-symmetrical swinging motions indeed are natural movements, though not significantly more than the symmetrical.

Overall these results show a promising result, that it is possible to apply natural movements within a virtual environment which are not possible through the standard MBT. However, as the experiment was conducted only with healthy participants the degree of using both legs might have been influenced, as their mobility of both legs cannot be compared to amputees.

6 CONCLUSIONS

One of the goals of this work was to test if the three chosen movements symmetrical swinging, anti-symmetrical swinging, and cycling, encouraged the use of both legs when playing the game. This was evaluated by counting the percentages of how much the participants used both legs in each game. The evaluation showed that all three games did encourage the use of both legs, as the symmetrical version resulted in 92.5%, the anti-symmetrical swinging resulted in 88.4% and the cycling resulted in 96%.

Another focus of the project was to compare if the anti-symmetrical movements were more natural to perform, compared to the standard symmetrical version. To this end, the use of both legs in the three versions was compared. This did not show any significant difference between the versions in using both legs. Furthermore, the versions were compared by having the participants rank the versions. Here, the anti-symmetrical swinging version was the favored version. This indicates that the anti-symmetrical swinging movements are at least as favorable to apply as the standard symmetrical. The cycling, however, was not well received and the participants did not find it easy to perform. The symmetrical and the anti-symmetrical swinging version did not seem to be too exhausting to perform. On the other hand, the cycling version was significantly more exhausting to perform. This finding suggests that the cycling version cannot be used for VR MBT, because the patients have to perform these exercises over a longer period of time. To address the issue of the cycling version, a physical pedal could be used where patients could feel some resistance while pushing the pedal. Furthermore, the patients would be guided by the pedal and would perform a correct sequence every time.

Overall, it can be concluded that anti-symmetrical swinging movements can be used in the same manner as symmetrical swinging movements in VR MBT for lower-limb amputees, which would not be possible through the standard physical MBT.

REFERENCES

Eric E. Brodie, Anne Whyte and Bridget Waller, 2003. Increased Motor Control of a Phantom Leg in Humans Results from the Visual Feedback of a Virtual Leg. *Neuroscience letters* 341, 2: 167-169.

Armel, K.C. and Ramachandran, V.S., 2003. Projecting sensations to external objects: evidence from skin conductance response. *Proceedings of the Royal Society of London B: Biological Sciences*, 270(1523), pp.1499–1506.

Bartal Henriksen, Ronni Nielsen, Laszlo Szabo, Nicaolaj Evers, Martin Kraus and Bo Geng, 2016. An Affordable Virtual Reality System for Treatment of Phantom Limb Pain. In: *VRIC*. VRIC 2016. Laval, France: ACM.

Botvinick, M., Cohen, J. and others, 1998. Rubber hands' feel'touch that eyes see. *Nature*, 391(6669), pp.756–756.

Brodie, E.E., Whyte, A. and Waller, B., 2003. Increased motor control of a phantom leg in humans results from the visual feedback of a virtual leg. *Neuroscience letters*, 341(2), pp.167–169.

Cole, J., Crowle, S., Austwick, G. and Slater, D.H., 2009. Exploratory findings with virtual reality for phantom limb pain; from stump motion to agency and analgesia. *Disability and Rehabilitation*, 31(10), pp.846–854.

Ehrsson, H.H., Spence, C. and Passingham, R.E., 2004. That's My Hand! Activity in Premotor Cortex Reflects Feeling of Ownership of a Limb. *Science*, 305(5685), pp.875–877.

Flor, H., 2002. Phantom-limb pain: characteristics, causes, and treatment. *The Lancet Neurology*, 1(3), pp.182–189.

Gallagher, S., 2000. Philosophical conceptions of the self: implications for cognitive science. *Trends in cognitive sciences*, 4(1), pp.14–21.

H. Henrik Ehrsson and Zakaryah Abdulkarim, n.d. No causal link between changes in hand position sense and feeling of limb ownership in the rubber hand illusion. *Atten Percept Psychophys*, [online] 2015. Available at: <http://130.237.111.254/ehrsson/pdfs/Abdulkarim&Ehrsson2015inpress.pdf>.

Kooijman, C.M., Dijkstra, P.U., Geertzen, J.H., Elzinga, A. and van der Schans, C.P., 2000. Phantom pain and phantom sensations in upper limb amputees: an epidemiological study. *Pain*, 87(1), pp.33–41.

Llobera, J., Sanchez-Vives, M.V. and Slater, M., 2013. The relationship between virtual body ownership and temperature sensitivity. *Journal of The Royal Society Interface*, 10(85), p.20130300.

Mori, M., MacDorman, K.F. and Kageki, N., 2012. The Uncanny Valley [From the Field]. *IEEE Robotics Automation Magazine*, 19(2), pp.98–100.

Murray, C.D., Patchick, E., Pettifer, S., Howard, T., Caillette, F., Kulkarni, J. and Bamford, C., 2006. Investigating the efficacy of a virtual mirror box in treating phantom limb pain in a sample of chronic sufferers. *International Journal on Disability and Human Development*, [online] 5(3). Available at: <http://www.degruyter.com/view/j/ijdhd.2006.5.3/ijdhd.2006.5.3.227/ijdhd.2006.5.3.227.xml> [Accessed 7 Sep. 2016].

Nielsen, R., Henriksen, B., Kraus, M. and Geng, B., 2017. Comparison of Body Positions in Virtual Reality Mirror Box Therapy for Treatment of Phantom Limb Pain in Lower Limb Amputees. *Comparison of Body Positions in Virtual Reality Mirror Box Therapy for Treatment of Phantom Limb Pain in Lower Limb Amputees*, p.2.

Ortiz-Catalan, M., Sander, N., Kristoffersen, M.B., Håkansson, B. and Brånemark, R., 2014. Treatment of phantom limb pain (PLP) based on augmented reality and gaming controlled by myoelectric pattern recognition: a case study of a chronic PLP patient. *Frontiers in Neuroscience*, [online] 8. Available at: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3935120/> [Accessed 5 Feb. 2016].

Osimo, S.A., Pizarro, R., Spanlang, B. and Slater, M., 2015. Conversations between self and self as Sigmund Freud—A virtual body ownership paradigm for self counselling. *Scientific Reports*, [online] 5(1). Available at: <http://www.nature.com/articles/srep13899> [Accessed 20 May 2017].

Osumi, M., Ichinose, A., Sumitani, M., Wake, N., Sano, Y., Yozu, A., Kumagaya, S., Kuniyoshi, Y. and Morioka, S., 2017. Restoring movement representation and alleviating phantom limb pain through short-term neurorehabilitation with a virtual reality system. *European Journal of Pain*, 21(1), pp.140–147.

Ramachandran, V.S. and Hirstein, W., 1998. The perception of phantom limbs. The DO Hebb lecture. *Brain*, 121(9), pp.1603–1630.

Ramachandran, V.S. and Rogers-Ramachandran, D., 1996. Synaesthesia in phantom limbs induced with mirrors. *Proceedings of the Royal Society of London B: Biological Sciences*, 263(1369), pp.377–386.

Sato, K., Fukumori, S., Matsusaki, T., Maruo, T., Ishikawa, S., Nishie, H., Takata, K., Mizuhara, H., Mizobuchi, S., Nakatsuka, H., Matsumi, M., Gofuku, A., Yokoyama, M. and Morita, K., 2010. Nonimmersive Virtual Reality Mirror Visual Feedback Therapy and Its Application for the Treatment of Complex Regional Pain Syndrome: An Open-Label Pilot Study. *Pain Medicine*, 11(4), pp.622–629.

Sherman, R.A., Sherman, C.J. and Parker, L., 1984. Chronic phantom and stump pain among american veterans: results of a survey: *Pain*, 18(1), pp.83–95.

Slater, M., Pérez Marcos, D., Ehrsson, H. and Sanchez-Vives, M.V., 2009. Inducing illusory ownership of a virtual body. *Frontiers in neuroscience*, 3, p.29.

Trojan, J., Diers, M., Fuchs, X., Bach, F., Bekrater-Bodmann, R., Foell, J., Kamping, S., Rance, M., Maaß, H. and Flor, H., 2013. An augmented reality home-training system based on the mirror training and imagery approach. *Behavior Research Methods*, 46(3), pp.634–640.

Tsakiris, M., Carpenter, L., James, D. and Fotopoulou, A., 2010. Hands only illusion: multisensory integration elicits sense of ownership for body parts but not for non-corporeal objects. *Experimental Brain Research*, 204(3), pp.343–352.

Zweighaft, A.R., Slotness, G.L., Henderson, A.L., Osborne, L.B., Lightbody, S.M., Perhala, L.M., Brown, P.O., Haynes, N.H., Kern, S.M., Usgaonkar, P.N. and others, 2012. A physical workstation, body tracking interface, and immersive virtual environment for rehabilitating phantom limb pain. In: *Systems and Information Design Symposium (SIEDS), 2012 IEEE*. [online] IEEE, pp.184–189. Available at: <http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6215131> [Accessed 29 Feb. 2016].